



SCIENCE & TECHNOLOGY OFFICE



**MSFC's Advanced Space Propulsion  
Formulation Task**

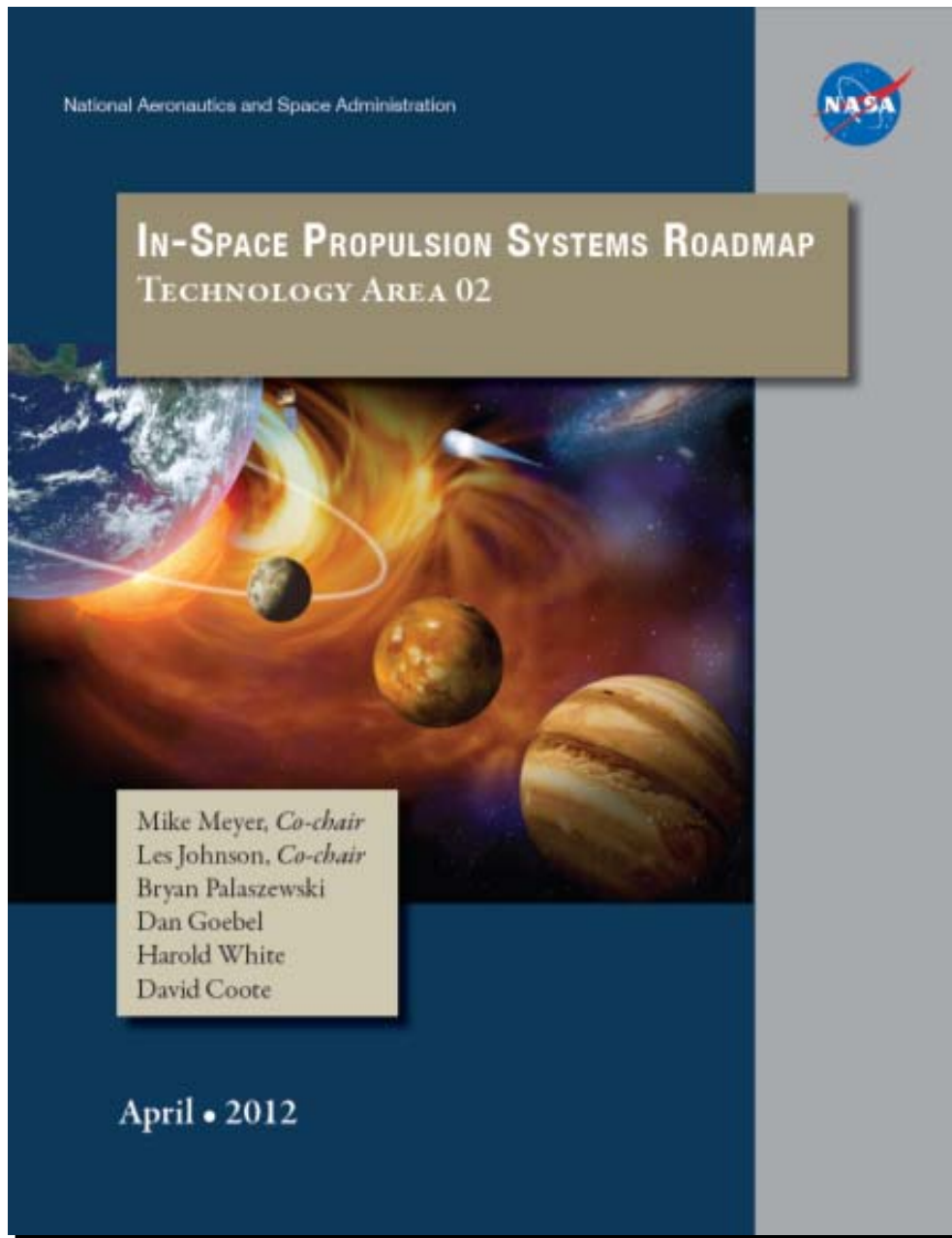
Lawrence D. Huebner, Harold P. Gerrish,  
Joel W. Robinson, and Terry L. Taylor  
Marshall Space Flight Center

19<sup>th</sup> Advanced Space Propulsion Workshop  
George C. Marshall Space Flight Center  
November 27-29, 2012

- Purpose
- Background
- Task Activity
- Sample Results
- Information Access

# Formulation Task Purpose

- Provide NASA Space Technology Program (STP) and Office of the Chief Technologist (OCT) with a knowledge base on advanced space propulsion technologies
  - Furnishes next layer of detail for technologies summarized in NASA's In-Space Propulsion Systems Roadmap, Technology Area 02 (TA-02)
  - Supports STP/OCT on where investments should be made
    - Enable good strategic decision making
  - Allows for better utilization of STP/OCT resources by giving context to any past, current, or proposed in-space propulsion technology development efforts in terms of:
    - Performance capability
    - Technology Readiness Level
    - Focus on those with potentially major impacts



- 45 Technologies were identified in NASA's In-Space Propulsion Systems Roadmap, Technology Area 02 (TA-02)
- TA-02 roadmap divided into four basic groups
  - (1) Chemical Propulsion
  - (2) Non-chemical Propulsion
  - (3) Advanced (TRL<3) Propulsion Technologies
  - (4) Supporting Technologies (pertinent technical areas strongly coupled with these groups which could allow significant improvements in performance)
- TA-02 Roadmap limited to 30 pages; more information needed to better understand each concept
- 25 of 45 were studied during this formulation task
  - Emphasis was on groups (3) and (2)

## 1.0 Chemical Propulsion

- 1.01 Monopropellants
- 1.02 Bipropellants
- 1.03 High-Energy Propellants
- 1.04 High-Energy Oxidizers
- 1.05 LOX/Methane Cryogenic
- 1.06 LOX/LH2 Cryogenic
- 1.07 Gelled and Metalized-Gelled Propellants
- 1.08 Solid Rocket Propulsion Systems
- 1.09 Hybrid Rockets
- 1.10 Cold Gas/Warm Gas Systems
- 1.11 Solid Micropropulsion
- 1.12 Solid Cold Gas/Warm Gas Micropropulsion Systems
- 1.13 Hydrazine or Hydrogen Peroxide Monopropellant Micropropulsion

## 2.0 Nonchemical Propulsion

- 2.01 Resistojets
- 2.02 Arcjets
- 2.03 Ion Thrusters
- 2.04 Hall Thrusters
- 2.05 Pulsed Inductive Thrusters
- 2.06 Magnetoplasmadynamic Thrusters
- 2.07 Variable Specific Impulse Magnetoplasma Rocket
- 2.08 Microresistojets
- 2.09 Teflon Microcavity Discharge
- 2.10 Micropulse Plasma
- 2.11 Miniature Ion/Hall

## 2.0 Nonchemical Propulsion (Continued)

- 2.12 MEMS Electropray
- 2.13 Solar Sail Propulsion
- 2.14 Solar Thermal
- 2.15 Nuclear Thermal
- 2.16 Electrodynamic Tether
- 2.17 Momentum Exchange Tether

## 3.0 Advanced Propulsion Technologies

- 3.01 Beamed Energy Propulsion
- 3.02 Electric Sail Propulsion
- 3.03 Fusion Propulsion
- 3.04 Metallic Hydrogen
- 3.05 Atomic Boron/Carbon/Hydrogen
- 3.06 High Nitrogen Compounds (N4+, N5+)
- 3.07 Antimatter Propulsion
- 3.08 Gas Core Fission
- 3.09 Fission Fragment
- 3.10 External Pulsed Plasma Propulsion
- 3.11 Breakthrough Propulsion Physics

## 4.0 Supporting Technologies

- 4.01 Engine Health Monitoring and Safety
- 4.02 Propellant Storage, Transfer & Gauging
- 4.03 Materials & Manufacturing Technologies
- 4.04 Heat Rejection
- 4.05 Power

## Technologies Addressed in Formulation Task

### 1.0 Chemical Propulsion

- 1.01 Monopropellants
- 1.02 Bipropellants
- 1.03 High-Energy Propellants
- 1.04 High-Energy Oxidizers
- 1.05 LOX/Methane Cryogenic
- 1.06 LOX/LH2 Cryogenic
- 1.07 Gelled and Metalized-Gelled Propellants
- 1.08 Solid Rocket Propulsion Systems
- 1.09 Hybrid Rockets
- 1.10 Cold Gas/Warm Gas Systems
- 1.11 Solid Micropropulsion
- 1.12 Solid Cold Gas/Warm Gas Micropropulsion Systems
- 1.13 Hydrazine or Hydrogen Peroxide Monopropellant Micropropulsion

### 2.0 Nonchemical Propulsion

- 2.01 Resistojets
- 2.02 Arcjets
- 2.03 Ion Thrusters
- 2.04 Hall Thrusters
- 2.05 Pulsed Inductive Thrusters
- 2.06 Magnetoplasmadynamic Thrusters
- 2.07 Variable Specific Impulse Magnetoplasma Rocket
- 2.08 Microresistojets
- 2.09 Teflon Microcavity Discharge
- 2.10 Micropulse Plasma
- 2.11 Miniature Ion/Hall

### 2.0 Nonchemical Propulsion (Continued)

- 2.12 MEMS Electropray
- 2.13 Solar Sail Propulsion
- 2.14 Solar Thermal
- 2.15 Nuclear Thermal
- 2.16 Electrodynamic Tether
- 2.17 Momentum Exchange Tether

### 3.0 Advanced Propulsion Technologies

- 3.01 Beamed Energy Propulsion
- 3.02 Electric Sail Propulsion
- 3.03 Fusion Propulsion
- 3.04 Metallic Hydrogen
- 3.05 Atomic Boron/Carbon/Hydrogen
- 3.06 High Nitrogen Compounds (N4+, N5+)
- 3.07 Antimatter Propulsion
- 3.08 Gas Core Fission
- 3.09 Fission Fragment
- 3.10 External Pulsed Plasma Propulsion
- 3.11 Breakthrough Propulsion Physics

### 4.0 Supporting Technologies

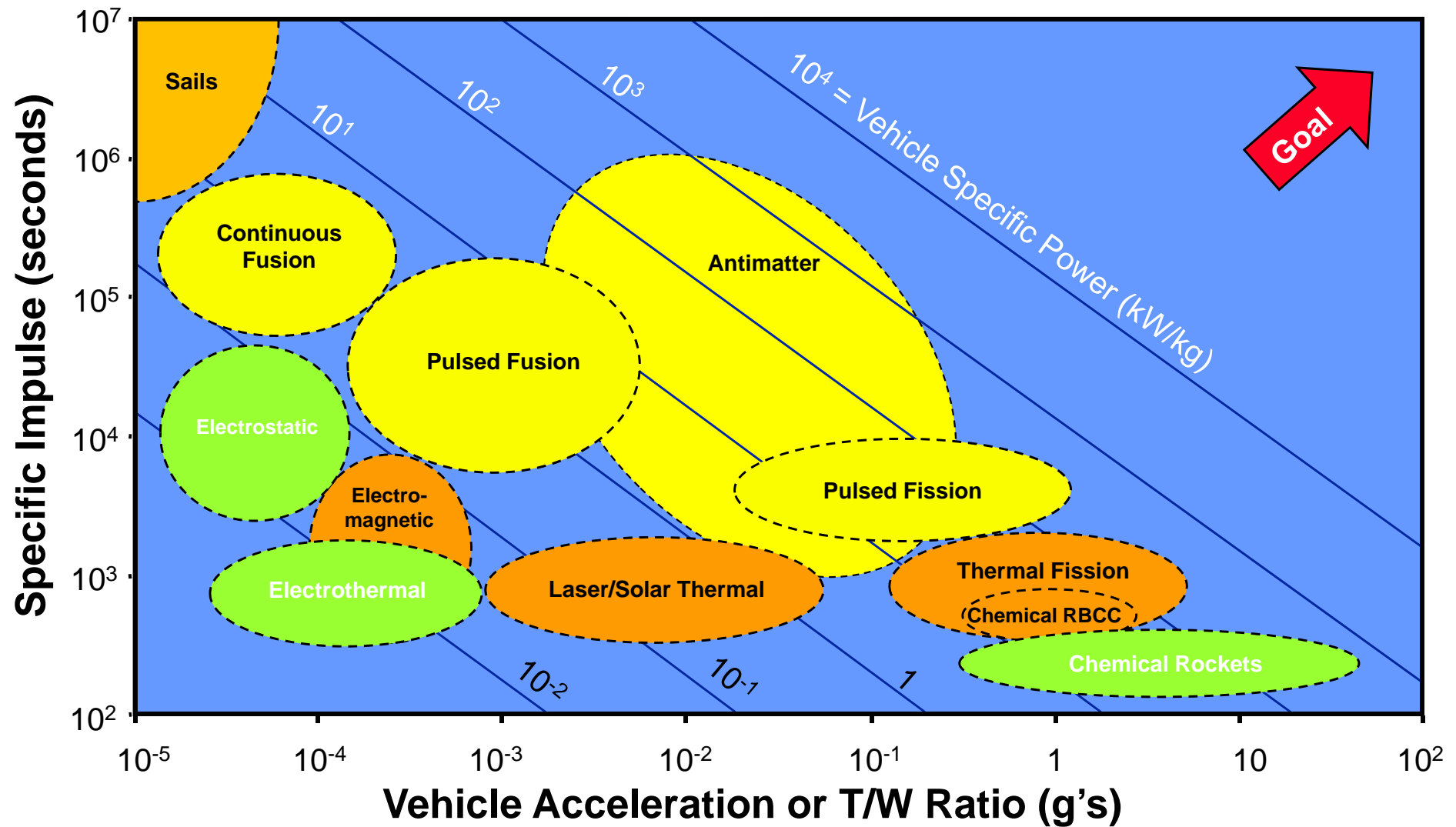
- 4.01 Engine Health Monitoring and Safety
- 4.02 Propellant Storage, Transfer & Gauging
- 4.03 Materials & Manufacturing Technologies
- 4.04 Heat Rejection
- 4.05 Power



# Task Activity

- **Map relevant existing technology and R&D efforts that NASA funds on Space Propulsion Concepts chart to identify gaps**
- **Generate Summary Report and one-page Summary Chart for each technology that includes:**
  - Narrative Description of technology with images depicting concepts and technology current state of the art (laboratory, flight experiments, etc)
  - Mission Applications and/or benefits of using concept compared to existing chemical systems
  - Identification of professional experts (by Name and Organization)
  - Description of past or current efforts at NASA, DoD, and universities
  - Identification of supporting subsystem or component technology hurdles (if applicable) needing development for this propulsion system concept to be feasible
    - Some these may be shared by multiple concepts, increasing its importance
  - Estimate of financial investment with each concept to date (if available)

# Space Propulsion Concepts



● Unproven Technology (TRL 1-3)
 ● Demonstrated Technology (TRL 4-6)
 ● Operational Systems (TRL 7-9)



# Mapping of Early FY12 NASA Efforts

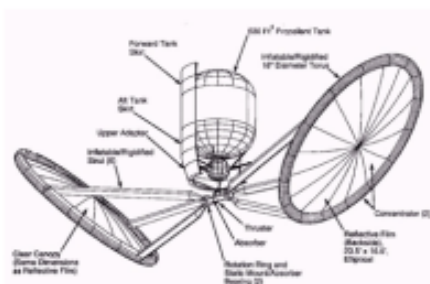
Category/Award	AES	Grants	SBIR	STTR	TDM	NIAC	Other	ISP	<i>Total</i>
Chemical Rockets	2	2	2			1		1	8
<b>Chemical RBCC</b>									0
Thermal Fission	1		2						3
Pulsed Fission						1			1
Antimatter			1						1
<b>Laser/Solar Thermal</b>									0
Pulsed Fusion			1						1
Electrothermal			1						1
Electro-Magnetic		4	2	1				1	8
Electrostatic		2	2					2	6
Continuous Fusion			1			2			3
Sails					1	1	2		4

AES: Advanced Exploration Systems  
 SBIR: Small Business Innovative Research  
 STTR: Small Business Technology Transfer  
 TDM: Technology Demonstration Missions  
 NIAC: NASA Innovative Advanced Concepts  
 ISP: OCT In-Space Propulsion Project

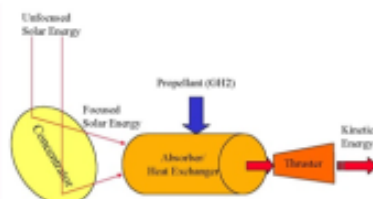
# Sample Summary Chart

## Solar Thermal Propulsion (STP)

### Propulsion System Description



The STP system takes the unfocused solar energy impinging on a large collector/concentrator and transforms it into kinetic energy of a propellant for thrust from direct heating of the propellant or indirect heating via heat exchanger.



### Mission Applications/Benefits (compared with off-shelf chemical)

STP was primarily considered as an upperstage to take payloads from low-earth-orbit (LEO, ~200 miles altitude) to geosynchronous earth orbit (GEO, ~22,000 miles altitude). Having a specific impulse (~900 seconds with hydrogen) about twice that of conventional chemical in-space engines allows for more payload weight on the launch vehicle. However, the volume of liquid hydrogen took up more volume in the payload shroud and the thrust level was 2-4 lbs, meaning the time for a LEO to GEO transfer mission was ~30 days. Others considered STP applications include using the heat from the system as bi-modal for electric power generation and as a transfer stage to the moon and other solar system destinations. More thrust than most electric propulsion concepts.

### Subsystem State of the Art

**Thruster**- Most thruster work in the past involved ground testing indirect solar heating as direct gain or thermal storage. Thrust range 0.5 – 2 lbs, Isp 700-860 seconds with hydrogen. Materials tested Tungsten, Tungsten/Rhenium alloys, Rhenium, Rhenium coated graphite. Experiments with carbides and carbide coatings. Temperature goal 2700-3000K. More testing needed to verify performance holds up to mission requirements.

**Concentrator**-Inflatable reflectors show the best promise made of polyimide CP to withstand space environment effects. Deployment of 4m x 6m off-axis parabolic inflatable reflector from storage package has been demonstrated to 50-60% efficiency.

**Propellant Utilization**-Controlled 30 day boil-off of liquid hydrogen to pressure feed the thruster has been demonstrated.

### Technical/Development Hurdles

Challenges are optical concentrator accuracy and performance (improving from 50-60% to 85-90%), system/stage packaging, sun pointing (subarcsec accuracy in flat, 1 cm by 1 cm packages), inflatable deployment, controlled cryogenic boil-off, and engine performance. An integrated overall system test has never been performed. Concept TRL~4

STP is limited by payload shroud volume when considering liquid hydrogen LH2. Options to overcome this hurdle include the use of high temperature carbides with melting point ~4200K.

### Recommendations

- Possible ways for STP to again be considered:
- Increase in Isp above 900 seconds using hydrogen. This requires high temperature carbides with melting points ~4200K. Operating a higher temperature increases the Isp to about 1200 seconds and allows more dissociation of the hydrogen.
  - Utilize a liquid hydrogen fuel depot or tanker in orbit to refill a smaller propellant tank or fill deployable tanks.
  - Other propellants showing significantly better performance than chemical and better storage than hydrogen.

### Subject Matter Experts:

Harold Gerrish (NASA-MSFC)  
Mike Holmes (Air Force)

## Information Included for Each Concept

- Summary
- Conclusions and Recommendations
- Typical Schematics
- Applications
- Benefits

### Summary:

Solar Thermal Propulsion (STP) effectively bridges the performance gap between chemical and electric propulsion by offering higher specific impulse options and higher thrust-to-weight ratios than electrical systems. STP requires only one propellant, and combines low thrust (<10 N) with moderate propulsion efficiency (300 sec. specific impulse). The system takes the unfocused solar energy impinging on a collector concentrator and transforms it into kinetic energy of a hydrogen-working fluid.

Two types of solar heating: (a) direct solar heating and (b) indirect solar heating. (a) Direct solar heating has incident solar radiation focused by the concentrator and directed into a receiver which then transfers heat to the propellant. The receiver energy is transferred to the propellant, which flows through an electric preheating or absorber cavity. The lowest propellant is then thermodynamically expanded in a nozzle to produce thrust. Direct gain transfer heat the propellant at the same time sunlight from the absorber cavity. Storage transfer heat the storage block first, then use propellant at a later time without sunlight. Indirect solar heating has the propellant absorbing the energy directly from the sunlight and requires a radiation shield. Indirect work done in the past was with indirect solar heating.

Solar thermal propulsion was conceived in 1959 by **Keith Dugan**. This was acknowledged by the National Research Council's panel on small spacecraft technology. The panel reported the following: "Adaptation of solar energy as a power source... research and technology programs... to demonstrate fully the capability of solar thermal systems." The panel went on to state that, "Space flight now needs to be constrained to explore deployment mechanisms and dynamics, vehicle packaging techniques and demonstrate the system performance and flexibility of the diverse thrust operations with the deployment system."

Secondary concentrators attached to the thruster can help focus more sunlight inside the absorber cavity and reduce the thermal requirements on the primary concentrator and can reduce the size of the receiver/absorber cavity opening to reduce heat and infrared signature loss. Reflective and refractive secondary concentrators have worked on in the past.

The concentrator can be a reflector or Fresnel lens. Rigid concentrators can be made, but are heavy and take up relatively periodic volume. Flat work needed more as reflective concentrators, which are light weight and can be folded and packaged into a small container. The best material was found to be a polycarbonate CP which is clear. A flat coating of Aluminum is used to be a reflector. Many light weight materials (e.g., Mylar) have been considered for the STP, but polycarbonate CP could withstand the space environment effects (e.g., exposure to charged particles and UV radiation) loss and maintain specular reflectivity. A lot of thin film reflective materials would be applicable with solar sails has been performed in the past. Many work is needed with materials which can inflate and then become rigidized with UV exposure. This avoids

### Typical Schematic:

concentrator with parabolic or reflective to collect from microsecond, white before

of the high leg compared to... surface with 104 seconds... on full-off with added heat... at 23 g/sec and avoiding... to maintain the 10 bar



70% Efficiency

- Limitations
- Previous NASA SBIR/STTR Awards
- Previous DOD SBIR/STTR Awards
- Currently Availability
- Flight/Test Heritage

- Results of this task need wide dissemination
  - Ease of use by STP/OCT
  - Access to interested researchers and Subject Matter Experts
- Plan to utilize a web-based system
  - Examples being investigated:
    - NASA TechPort
    - MSFC Propulsion Databook
  - Allows for easy access, review, and updating
    - “Living” document

# Summary

- Formulation task was performed in FY12 to provide additional substance, depth, and activity knowledge to technology areas identified in TA-02, In-Space Propulsion Systems Roadmap
  - 25 of 45 TA-02 Technologies were studied
- Not a complete catalog but attempted to make results objective and factual
- Information is considered in a “draft” state
  - Recommending SMEs and others working in these areas review and provide updates
- Utilize information to develop proposals of promising advanced propulsion technologies

# Acknowledgements

- The following individuals are duly noted for their execution of the formulation task
  - Joel Robinson, Task Manager
  - Harold Gerrish, Technical Reviewer
  - Les Johnson, Technical Reviewer
  - Dan Thomas, Technical Reviewer
  - Adam Butt, Technical Reviewer
  - Tony Robertson, Technical Reviewer